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Nutrient Criteria: Considerations for Corps of Engineers Reservoirs

by Robert H. Kennedy

PURPOSE: This technical note describes requirements recently established by the U.S. Environmental Protection Agency (EPA) to determine nutrient criteria for lakes and reservoirs. The technical note also examines proposed methodological approaches, and discusses their relevance to Corps of Engineers water quality and environmental management activities.

BACKGROUND: Renewed concern over the adverse impacts of nutrients on the quality of surface waters prompted drafting of the Vice President's Clean Water Action Plan (Browner and Glickman 1998) and led to the design of the EPA's national strategy for the development of regional nutrient criteria for major classes of water bodies, including rivers and streams, lakes and reservoirs, wetlands, and estuaries and coastal waters (U.S. Environmental Protection Agency 1998). Development of such a strategy is founded on the well-established relationship between plant nutrients, particularly phosphorus and nitrogen, and water resource impairment (e.g., National Academy of Sciences (1969)). Implicit in the strategy is the importance of the linkage between nutrient sources in the watershed and resultant concentrations in receiving waters. The strategy is clearly intended to limit or reduce water quality problems related to nutrient overenrichment from the watershed. Once developed, nutrient criteria can be used for management planning and to establish standards and set limits for National Pollution Discharge Elimination System (NPDES) permits and for Total Maximum Daily Load (TMDL) targets (U.S. Environmental Protection Agency 1991).

In general, the strategy requires identification of reference or minimally impacted water bodies and their associated nutrient levels under the assumption that such nutrient levels can serve as criteria for all similar water bodies in the same geographic region. The process will be initiated within each EPA Region and by ecoregion (Omernik 1987) or geographic regions anticipated to have similar influences on water quality. The second step involves refinements to address differences between states in the same region, and the setting of criteria.

Development of a nutrient criteria strategy by the EPA coincides with increasing concerns over the quality of water associated with Corps water resource development projects and ongoing Corps efforts to ensure that water quality goals are met. Described here are (1) the proposed methodology for developing nutrient criteria, (2) considerations unique to their development for Corps reservoirs, and (3) recommendations for Corps involvement in the development process.

PROPOSED APPROACH FOR DEVELOPING NUTRIENT CRITERIA: The currently proposed EPA approach for the development of nutrient criteria for lakes and reservoirs involves the following steps:[1]

1. Establish regional technical assistance groups.

2. Delineate nutrient ecoregions.

3. Classify or group lakes/reservoirs using non-nutrient criteria.

4. Establish an appropriate nutrient-related database.

5. Establish reference conditions.

6. Develop nutrient criteria.

Establishing regional technical assistance groups (RTAGs) in each EPA region provides a link to appropriate specialists (e.g., limnologists, resource managers, hydrologists, ecologists, etc.) with knowledge of area lakes and reservoirs. The membership of the RTAG, which may include experts from other federal or state agencies having water resource management responsibilities in the region, should be such that objective evaluations and recommendations are assured. The intent of the RTAG is to provide a sound technical basis for decision-making and criteria formulation.

Omernik (1987) developed maps of ecological regions or ecoregions of the conterminous United States (Figure 1). Ecoregion boundaries are delineated primarily according to physiographic characteristics but have been demonstrated to account for geographic differences in the quality of aquatic resources (e.g., Wilson and Walker (1989)). A major responsibility of the RTAG will be to assess regional water quality databases as a means to establish and refine nutrient ecoregions. Establishing nutrient ecoregions may result in a subdividing of current ecoregions or in the shifting of existing boundaries. The primary source of such information will be the EPA's STORET database, since state and federal agencies are now required to submit data on a routine basis. Other potential data sources include the EPA's National Eutrophication Survey (NES) and National Surface Water Survey (NSWS) databases, studies conducted as part of the Clean Lakes Program (CLP) or Environmental Monitoring and Assessment Program (EMAP), utility companies, citizen monitoring groups, and state, tribal, or federal agencies. Despite the long-acknowledged importance of nutrients in determining the quality of surface waters, some regions may lack sufficient data for describing nutrient conditions, and will require the collection of additional or supplemental data.

Recognizing that water bodies may exhibit differing responses to nutrient inputs, the proposed approach requires that lakes and reservoirs be classified or grouped based on nonnutrient characteristics that potentially influence trophic responses. For instance, the presence of non-algal turbidity (e.g., suspended inorganic solids) strongly influences relationships between nutrient availability and algal growth (e.g., Smith (1990), Walker (1982)), suggesting that lakes located in watersheds having highly erodible soils be grouped together for the purpose of developing nutrient criteria.

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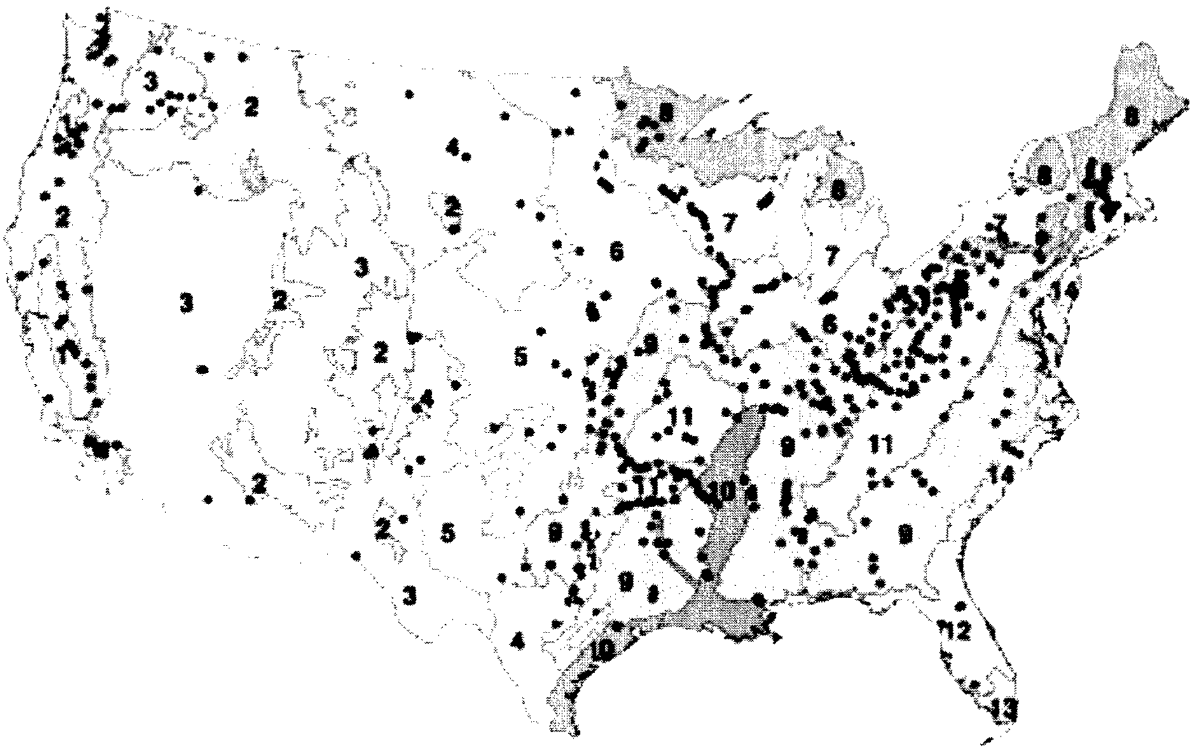
1 Personal Communication, 2000, Dr. George Gibson, U.S. Environmental Protection Agency, Washington, DC.



1 = Willamette & Central Valleys; 2 = Western Forested Mountains; 3 = Xeric West; 4 = Great Plains Grass & Shrublands; 5 = South Central Cultivated Great Plains; 6 = Corn Belt & Northern Great Plains; 7 = Mostly Glaciated Dairy Region; 8 = Nutrient Poor Largely Glaciated Upper Midwest & Northeast; 9 = Southeastern Temperate Forested Plains & Hills; 10 = Texas-Louisiana Coastal & Mississippi Alluvial Plains; 11 = Central & Eastern Forested Uplands; 12 = Southern Coastal Plain; 13 = Southern Florida Coastal Plain; 14 = Eastern Coastal Plain

Figure 1. Map of the nutrient ecogions of the conterminous United States. Symbols indicate the locations of Corps dams. Ecoregional boundaries based on Omernik (1987)

Other nonnutrient characteristics useful for identifying subgroups include lake or watershed area, lake volume or depth, lake origin (e.g., glacial versus flood plain lakes), and nonnutrient water chemistry (e.g., color, dissolved organic matter, or pH).

Setting a nutrient criterion will be based on the following five considerations:

1. ***An investigation of the historical record.*** Current and historical information allow description of the current status of the resource.

2. ***Establishment of a reference condition.*** Reference conditions, or those conditions anticipated to occur in the absence of or with minimal anthropogenic influences, describe the best possible resource status for the region.

3. ***The use of models.*** Models, when appropriately calibrated and verified, are used to provide information when existing data are limited or unavailable.

4. ***Expert assessment of the information.*** The RTAG provides an objective and comprehensive interpretation of all information for the establishment of the optimal nutrient criterion for the region.

5. ***Attention to downstream effects.*** This element requires that no nutrient criteria for upstream waters can produce unacceptable water quality in downstream waters. Should such be the case, the criterion for upstream waters must be modified accordingly.

Since few water bodies are totally free from such influences, identifying reference conditions (as in No. 2 above) will be a crucial step in the nutrient criteria development process and may involve identification of desirable or least-impacted conditions. This is particularly true for reservoirs. Three approaches for establishing reference conditions are proposed:

1. ***Direct observation of current or historic nutrient conditions.*** This approach is based on (a) meeting the subjective requirement of limited anthropogenic influence, or (b) a statistical (e.g., frequency analysis) assessment in which minimally impacted sites are identified.

2. ***Paleolimnological reconstruction.*** This approach involves analyses of dated sediment cores (e.g., identification of diatom frustules or fossil pigments) as a means to infer past nutrient conditions.

3. ***Model prediction or extrapolation.*** This approach uses empirical or deterministic models to estimate lake conditions based on anticipated or ideal loading conditions, and is particularly useful in regions lacking sufficient observed data.

Recognition of the link between nutrient concentrations, trophic conditions, and resource use is implicit in the establishment of individual nutrient criteria. As such, response variables historically associated with cultural eutrophication are of concern. These include total phosphorus and total nitrogen concentrations, chlorophyll *a* concentration, and Secchi disk transparency. From a practical standpoint, acceptable levels for each of these variables will be identified in one of two ways: based on the lower quartile (25 percent) of the frequency distribution of concentrations for a regional set of lakes or the upper quartile (75 percent) of the frequency distribution of concentrations for the regional set of reference lakes. States and tribes may make these criteria more stringent to ensure that local requirements for designated uses (e.g., aquatic life, drinking water supply, outstanding natural resource waters, fisheries, etc.) are met, but cannot make them less stringent than the regional criterion.

CONSIDERATIONS FOR CORPS RESERVOIRS: Questions related to the development of nutrient criteria for reservoirs in general and Corps reservoirs in particular are presented and discussed below. Answers to these questions will profoundly influence future Corps water resource management efforts to address eutrophication-related issues and promote more meaningful participation by the Corps in the development of nutrient criteria.

What Constitutes a 'Reservoir,' How Do Reservoirs Differ, and Are They Necessarily Different Than 'Natural Lakes'? Hutchinson (1957) defined reservoirs as 1 of 76 lake types based on basin origin. The key distinguishing feature of reservoirs is the presence of a man-built dam. Since their structural and operational characteristics play important roles in defining the characteristics of impounded lakes (Kennedy et al. 1985, Kennedy 1999), the presence of a dam warrants consideration in any assessment of management-related questions. In the current context, is it reasonable to consider equally all lakes impounded by a dam when defining reference conditions? A related question is whether the presence of a dam necessarily distinguishes a reservoir from a natural lake relative to nutrient-related, trophic responses.

While dams are often assumed to have considerable height and to impound relatively large reservoirs, this is not a justifiable generalization. The National Inventory of Dams (NID) (U.S. Army Corps of Engineers 1998) contains descriptive information for approximately 65,000 public and private dams throughout the United States. Analysis of these data indicates a widely ranging (values from 1 to greater than 200 m) and skewed distribution in dam height with a median value of 8.1 m (Figure 2). A markedly different distribution is apparent when Corps dams are considered separately (Figure 2). While also skewed toward lower values, Corps dams exhibit a substantially higher median height (29.0 m). These differences in dam height imply broad differences in maximum water column depth across all reservoirs and indicate that reservoir-impounded Corps dams may exhibit disparate bathymetric characteristics. Because lake depth is an important summary parameter for phenomena influencing water quality (e.g., mixed layer depth, relative depth of the photic zone, etc.), the inclusion of all lakes created by the construction of a dam in a single class will result in a highly heterogeneous group. A high degree of heterogeneity will clearly make comparisons or identification of reference conditions difficult.

Comparative studies of large reservoirs, including Corps reservoirs, and natural lakes (Thornton et al. 1980, Wetzel 1990) allowed identification of factors uniquely influencing the limnology of reservoirs. In general, large reservoirs have more expansive drainage basins, larger volumes and surface areas, greater depth, and shorter water residence times than natural lakes. All of these attributes have significant implications for water quality responses. For example, larger drainage areas for reservoirs result in high areal nutrient and sediment loading rates, and more rapid flushing. High sediment loads decrease water clarity, thus reducing potential phytoplankton production, despite relatively high nutrient levels (Kimmel, Lind, and Paulson 1990; Kimmel and Groeger 1984; Kennedy, Thornton, and Gunkel 1982).

A similar comparison among reservoirs contained in the NID allows quantification of the range of physical dimensions for reservoirs and provides a new perspective on Corps and other large reservoirs. Reservoirs impounded by Corps dams have larger drainage areas, greater mean and maximum depths, larger surface areas and volumes, but similar ranges in water residence times (Figure 3). Given the well-established influence of these attributes on water quality conditions, these differences will be significant when considering the identification of homogeneous groups within which to identify reference conditions or establish nutrient criteria.

Dams allow for the storage and release of water, and operating dams to accomplish these water control goals has important secondary effects on the water quality of impounded lakes. Principal among these are influences on thermal budgets, thermal structure, mixing regime, and material

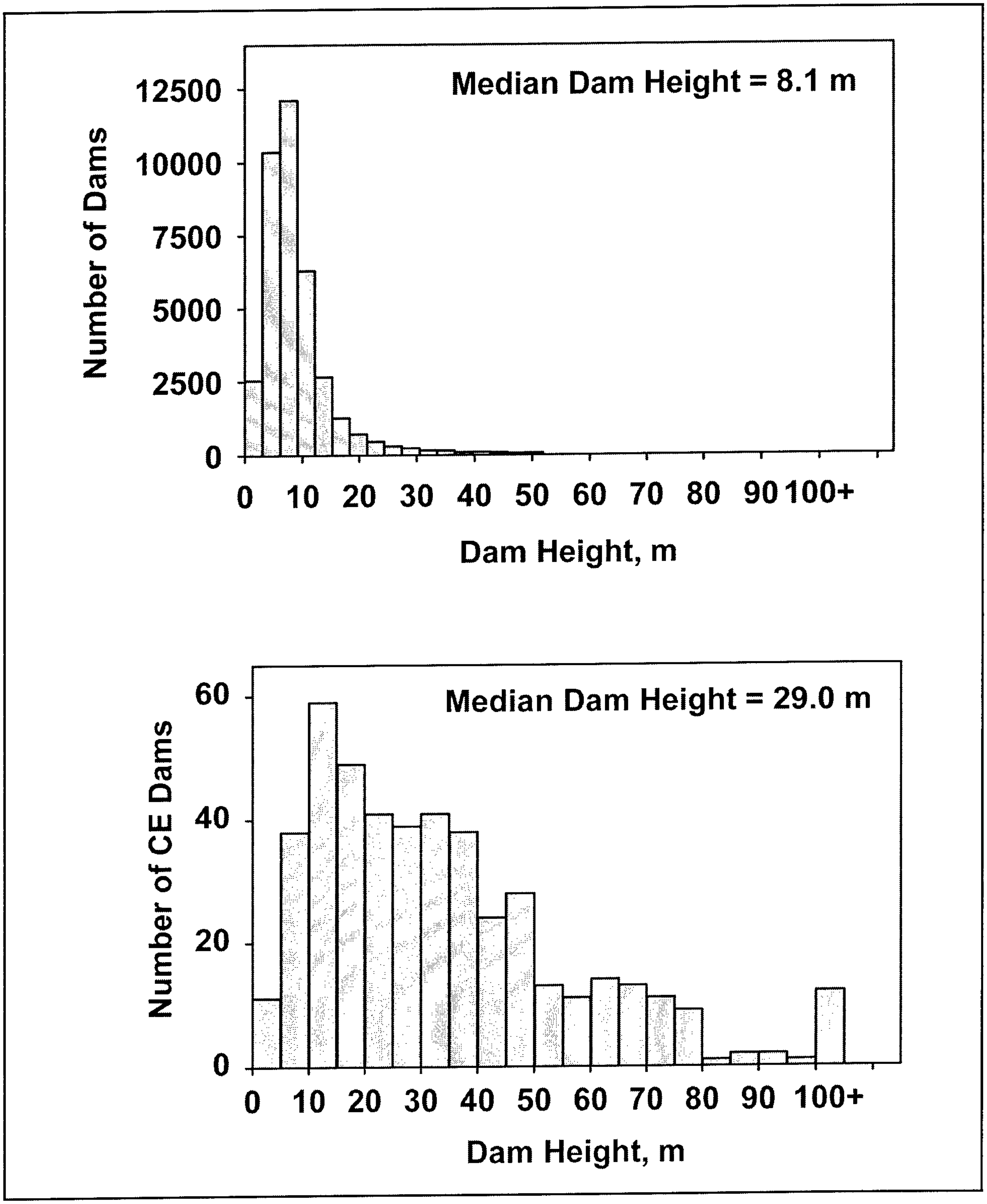


Figure 2. Frequency distribution of dam height for all U.S. dams (upper) and Corps dams (lower). Based on data included in the National Inventory of Dams (U.S. Army Corps of Engineers 1998)

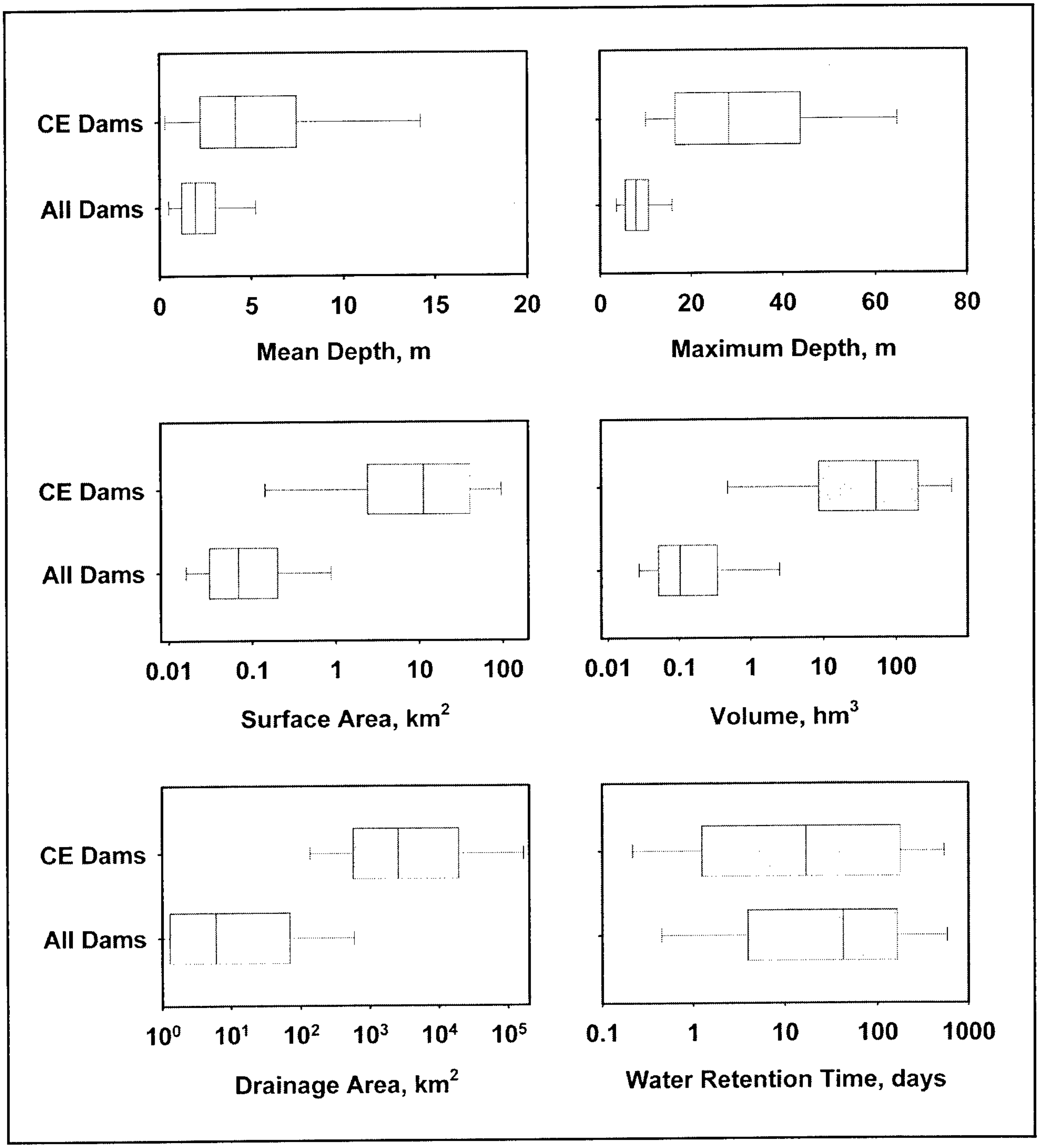


Figure 3. Comparison of selected physical attributes of reservoirs impounded by Corps dams and by all dams contained in the NID. Median values are indicated by a vertical line; bars indicate the 25th to 75th quartile range. Capped horizontal lines indicate the 5th to 95th quartile range

budgets. The influence of outlet depth on thermal budgets for reservoirs is well-documented (Kennedy and Walker 1990, Kennedy et al. 1985, Ford 1990). In general, the release of cool bottom waters through near-bottom gates results in heat storage, while surface releases dissipate heat by removing warm surface water (Martin and Arneson 1978). These differences can lead to marked differences in thermal structure throughout an annual thermal cycle. For instance, the change from

near-surface release to near-bottom release would result in pronounced warming of the water column and a deepening of the seasonal thermocline. Conversely, near-surface release would lead to the establishment of a seasonal thermocline similar to that for natural lakes of similar size located in the same climatic region. Both would function as overflow systems, dissipating heat and storing cool bottom waters. Such differences have important implications for trophic responses, since the depth of the thermocline will influence the depth of the mixed layer and the ratio of the mixed-layer depth to the depth of the photic zone, both of which influence phtyoplankton responses.

The depth of withdrawal also influences material budgets (Kennedy and Walker 1990, Wright 1967). Because lakes and reservoirs function as settling basins for particulate material and because their bottom waters are influenced by interaction with underlying sediments (e.g., nutrient release during periods of anoxia), release of bottom water can reduce material retention rates. When releases are from the surface, material retention increases. Therefore, the generalization that many bottom-release reservoirs may exhibit higher material dissipation than natural lakes and many surface-release reservoirs has important implications for the trophic responses to nutrient inputs.

Thus, a generalization that all lakes formed by the construction of a dam are deep and strongly influenced by operation of the dam is not fully appropriate. The categorization of all lakes formed by the construction of a dam would include a morphologically and hydrologically disparate group, some of which may respond to dam operation in a similar manner as would natural lakes. In many cases, it may be justifiable to group selected reservoirs with natural lakes when identifying reference conditions.

How Might Classes, Types, or Logical Groupings of Reservoirs Be Identified When Establishing Appropriate Reference Conditions for Corps Reservoirs? Relationships between why a dam is built, how and where it is built, how it is subsequently operated, and the characteristics of the resulting reservoir are reasonably well-defined (Kennedy 1999). With regard to the establishment of nutrient criteria, can we utilize these relationships to define appropriate groups within which to identify reference conditions? Three categories of reservoir characteristics seem germane for this purpose: location within a drainage basin; structural and operational characteristics of the dam; and hydraulic residence time.

a. ***Location in drainage basin.*** Decisions about where dams are located broadly define physical attributes of the resulting reservoir which, in turn, strongly influence its limnological character (Kennedy 1999). For example, tributary storage reservoirs are located on lower-order rivers in the upland areas of drainage basins and thus often reside in steeply sloping and dendritic basins with long, complex shorelines. Such reservoirs are frequently relatively deep and strongly stratified. Inflows are often lower on suspended sediment concentrations and may exhibit great seasonal or short-term variability. Changes in storage can result in marked changes in pool elevation, and water residence times are often long.

By contrast, run-of-the-river and mainstem storage reservoirs, frequently operated to meet navigation and hydropower objectives, are located on higher-order river reaches. Run-of-the-river reservoirs are often limited in lateral extent to the areas immediately adjacent to the original river channel and seldom experience frequent or extensive changes in pool depth. Because they are commonly located at the downstream extent of large drainage

basins, they receive high suspended sediment loads, are turbid, and flush rapidly. Dams for mainstem storage reservoirs, on the other hand, generally inundate broad river flood-plains, offering extensive storage volumes. Despite relatively high inflow rates, water residence times can be long due to the large potential storage volume. Moderate changes in pool depth occur and while inorganic turbidity levels in the reservoir are initially relatively high due to riverine influences, they are often subsequently reduced due to long water residence times.

Table 1 lists descriptive information for three Corps reservoirs on the Cumberland River illustrative of the potentially important relationships between reservoir purposes, location, and limnological characteristics. While actual differences in limnological characteristics between reservoirs will reflect local conditions and water control strategies in the drainage basin, it is clear that operational objectives are important determinants of many important reservoir characteristics, and should be considered when defining groups of reservoirs for identification of reference conditions or for development of nutrient criteria.

Table 1
Selected Physical Characteristics of Three Operationally Distinct Reservoirs on the Cumberland River in Tennessee and Kentucky

Characteristic	Barkley Reservoir	Cumberland Reservoir	J. Percy Priest Reservoir
Reservoir Type	Run-of-the-river	Mainstem Storage	Tributary Storage
Primary Purposes	Navigation/Power	Power/Flood Control	Flood Control/Power
Drainage Area, km^2	45,579	14,994	2,240
Volume, hm^3	1,072	4,928	484
Surface Area, km^2	234	203	58
Length, km	190	163	68
Shoreline Development	3.5	39.9	12.7
Water Retention, days	11	208	176
Mean Depth, m	4.8	23.3	8.4
Mixed Depth, m	4.8	8.1	5.5
Inorganic Turbidity, m^{-1}	1.23	0.47	0.30

b. ***Dam structure and operation***. The purpose(s) for which dams are built determine, in general, their structural design and how they will be operated. The location of outlet structures relative to the depth of the water column, as well as the thermal structure of the water column, determine the depth strata from which water is released. As was discussed previously, withdrawal depth can have significant implications for reservoir thermal cycles and the expression of trophic responses to changing nutrient levels. Thus, interactions between reservoir depth, depth from which water is released, the volume of water released and thermal structure of the water column must be considered when assessing relative similarities between reservoirs and lakes, or among reservoirs.

As engineered systems designed to accomplish specific, and often narrowly defined water control objectives, dams and the reservoirs they impound exhibit prescribed characteristics

dictated by functional requirements. Scheduling changes in reservoir volume (and, therefore, depth), for example, depends upon basin capacity, hydrology, and water uses. From an operational standpoint, this often involves the development and application of "rule curves," or predetermined changes in reservoir surface elevation. For tributary storage reservoirs, particularly those operated for flood control, rule curves frequently require the lowering of surface elevations as a means to allow storage of subsequent floodwaters, which may be retained for extended periods of time prior to their release downstream. The result is marked seasonal fluctuations in water column depth, reservoir volume, and water retention time.

Operational requirements for run-of-the-river reservoirs offer a contrasting example. Since the primary purpose of such reservoirs is navigation, reservoir surface elevations must be controlled within narrow limits. Thus, despite larger inflow volumes, rule curves for run-of-the-river reservoirs dictate minimal fluctuations in water column depth. In the absence of changes in water storage volume, water residence times are determined by hydrologic conditions and are uncoupled from dam operation.

Obvious from the above discussion and examples is the necessity to consider dam structure and operation when evaluating factors influencing the limnological attributes of reservoirs and the expression of trophic responses. In addition to their importance to the development of nutrient criteria, these relationships also describe potential management opportunities unique to reservoirs.

c. ***Hydraulic retention time.*** Hydraulic retention time, defined as lake or reservoir volume divided by outflow rate and expressed as days or years, strongly influences limnological processes in lakes and reservoirs (e.g., Straškraba et al. 1993). These influences include changes in material retention rates (Straškraba, Tundisi, and Duncan 1995; Kennedy 1998), modifications to thermal structure (Straškraba 1994), and impacts on the size and composition of planktonic communities (Straškraba and Straškrabova 1975; Søballe and Threlkeld 1985; Søballe and Bachmann 1984).

Residence times vary widely between natural lakes and reservoirs, and among reservoirs. Thornton et al. (1980) evaluated data for selected Corps reservoirs and lakes contained in the NES database, and reported significantly higher geometric mean values for lakes (270 days) than for reservoirs (135 days). A similar assessment of data included in the NID indicates a broad range in water residence time for reservoirs impounded by U.S. dams (Figure 3). Values for the nearly 65,000 reservoirs ranged from less than 1 day to over 750 days; a similar range was observed for those operated by the Corps. Many of those with short residence times are operated as run-of-the-river reservoirs for the purpose of navigation.

This broad range in residence times, and the acknowledged influences of residence time on many processes determining trophic responses, suggests the necessity to carefully consider water residence time when grouping reservoirs for the purpose of identifying reference conditions or developing nutrient criteria. The currently proposed EPA approach acknowledges the importance of water residence time and recommends that reservoirs with

times less than 14 days be included with rivers for the purpose of nutrient criteria development under the assumption that such short detention times would have a minimal influence on water quality. However, Ryding and Rast (1989) suggest that impoundment-related changes in water quality will occur when doubling times for algae are less than water residence time. Since Reynolds (1997) suggests that algal doubling rates are in the range of 0.5-1.5 day^{-1}, it is clear that nutrient-related influences on trophic state are possible at relatively short water residence times. For reservoirs with longer residence times, anticipated differences in trophic responses between natural lakes and reservoirs will be minimized. In such cases, it may be possible to include both natural lakes and reservoirs with similar water residence times, assuming broad similarities in other attributes, in the same group when establishing reference conditions or developing nutrient criteria. In regions with a limited number of reservoirs, this will allow increased sample size for statistical treatments of the data.

Based on the above considerations, a reasonable and defendable approach to the identification of appropriate groups of reservoirs would employ multiple descriptors based on operational and physical attributes. Suggested mensuration variables for each attribute are presented in Table 2.

Table 2
Categories and Attributes for a Composite Classification Approach for Corps Reservoirs, and Suggested Mensuration Variables

Category	Attribute	Measured Variable
Location and size	Watershed dimension	Drainage area Location of dam in hydrologic continuum
	Reservoir dimension	Surface area Volume Length Mean and maximum depth Shoreline development ratio
Hydrology	Hydraulic loading	Inflow and outflow rates Annual/seasonal hydraulic retention time
	Storage dynamics	Pool elevation/volume Change in pool elevation
Structure and operation	Dam design	Dam height Outlet depth (relative to water column depth)
	Dam operation	Quantity and seasonality of release volumes Depth of release
Other response effects	Light regime	Non-algal turbidity Photic depth to mixed depth ratio
	Mixing regime	Thermal stability Mixed layer depth

Taken together, this suite of physical and operational characteristics attempts to define factors influencing the expression of trophic responses to changing nutrient levels relative to reservoirs. For example, Figure 4 displays selected factors influencing trophic characteristics for six reservoirs located in the Cumberland River drainage basin, all of which exhibit differing physical characteristics based on differing operational requirements. The two run-of-the-river reservoirs, which are relatively shallow and rapidly flushed, are high in nutrients but exhibit a low value for the product of Secchi depth and chlorophyll (SD*CHL; Walker 1996), suggesting that light extinction and algal production are strongly influenced by inorganic turbidity. By contrast, the two tributary reservoirs, located in upstream areas of the drainage basin and having relatively long water residence times, have lower observed nutrient levels and exhibit a light regime (based on values of SD*CHL) more strongly influenced by algae than inorganic turbidity. Since such broad differences in trophic responses can be anticipated, great care must be taken when identifying homogeneous groups within which to identify reservoir reference conditions and to develop nutrient criteria.

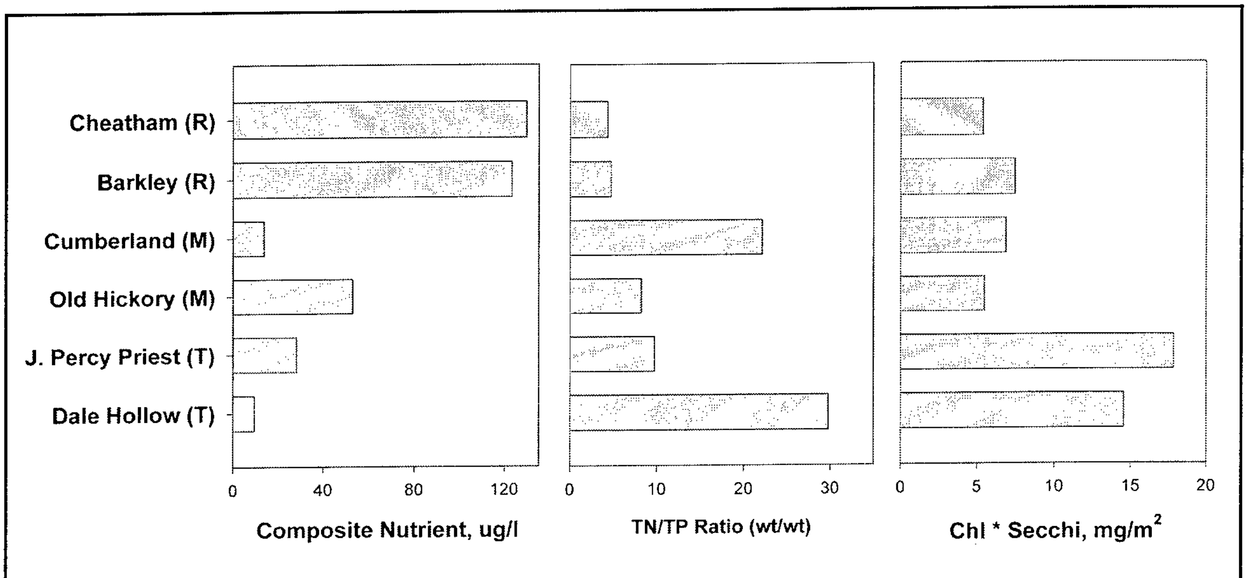


Figure 4. Comparison of selected trophic characteristics for representative tributary (T), mainstem storage (M), and run-of-the-river (R) reservoirs in the Cumberland River drainage basin. Composite nutrient is based on nutrient partitioning models and represents the relative availability of nitrogen and phosphorus (Walker 1985). Based on data from the NES database (USEPA 1978)

Since Reservoirs Exhibit Heterogeneity in Water Quality, Should Criteria Have Spatial Resolution? The construction of Corps and other large reservoirs on relatively large streams and rivers, and the location of the dam distant from the point of inflow provides a physical setting conducive to the establishment of longitudinal gradients in water quality (Kennedy et al. 1982). Reservoirs with large surface areas and limited circulation may also exhibit lateral or regional differences in water quality conditions. Losses of suspended sediment and particulate organic material by sedimentation lead to increasing water clarity with increasing distance from inflows, a phenomenon often influencing light regime and algal responses to nutrients. For stratified reservoirs, cool inflows sink below lake surface waters at the point (often referred to as the plunge point) at which buoyant forces exceed advective forces and progress through the water column as an

inter-flowing or under-flowing density current. Such currents transport inflowing materials, including nutrients, below the surface layer thereby reducing nutrient availability for algae at downstream locations (Kennedy and Walker 1990, Hejzlar and VyhàBlek 1999).

West Point Lake, a large (surface area = 105 km^2; volume = 746 hm^3; length = 53 km) Corps hydropower reservoir located on the Chattahoochee River 110 km downstream from Atlanta, GA, illustrates longitudinal gradients in water quality (Kennedy, Thorton, and Gunkel 1982; Kennedy et al. 1994). During September 1991, total phosphorus concentrations were initially high (approximately 100 ug/l) due to the influence of inflows from the Chattahoochee River, but declined precipitously along the longitudinal axis of the lake as a result of sedimentation and an inter-flowing density current (Figure 5). Similar, although less dramatic, gradients were observed for total nitrogen. Secchi depth transparency and chlorophyll concentration, while low in upstream reaches, exhibited marked increases at mid-reservoir coincident with the transition from riverine to lacustrine conditions.

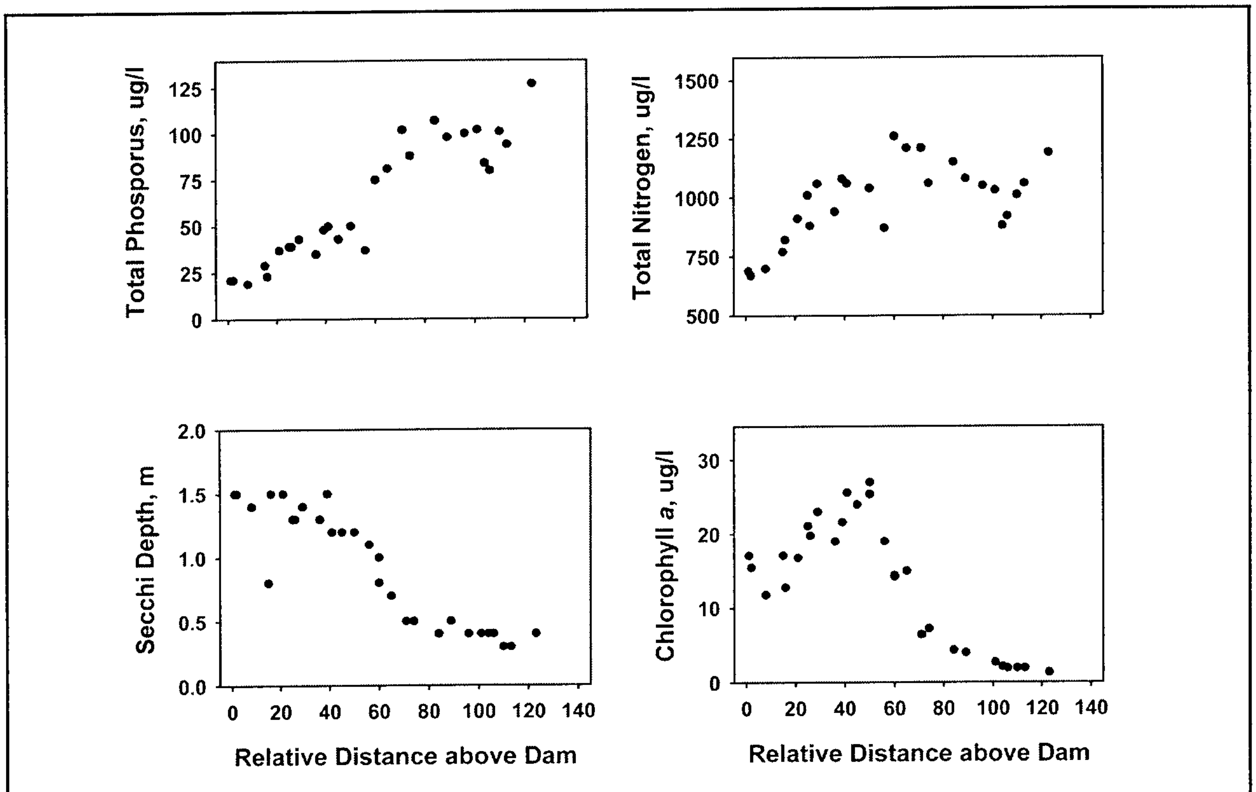


Figure 5. Longitudinal gradients in total phosphorus concentration, total nitrogen concentration, Secchi depth, and chlorophyll concentration in West Point Lake surface waters during September 1991. Based on data reported by Kennedy et al. (1994)

Perhaps of greater relevance to the issue of nutrient criteria and the explicit assumptions concerning linkages between nutrients and algae, are spatial differences in factors influencing trophic responses in West Point Lake (Figure 6). Total nitrogen to total phosphorus ratios increase markedly from upstream areas, which are marginally phosphorus limited, to strongly phosphorus-limited downstream areas. The product of Secchi depth and chlorophyll, an indicator of the partitioning of light

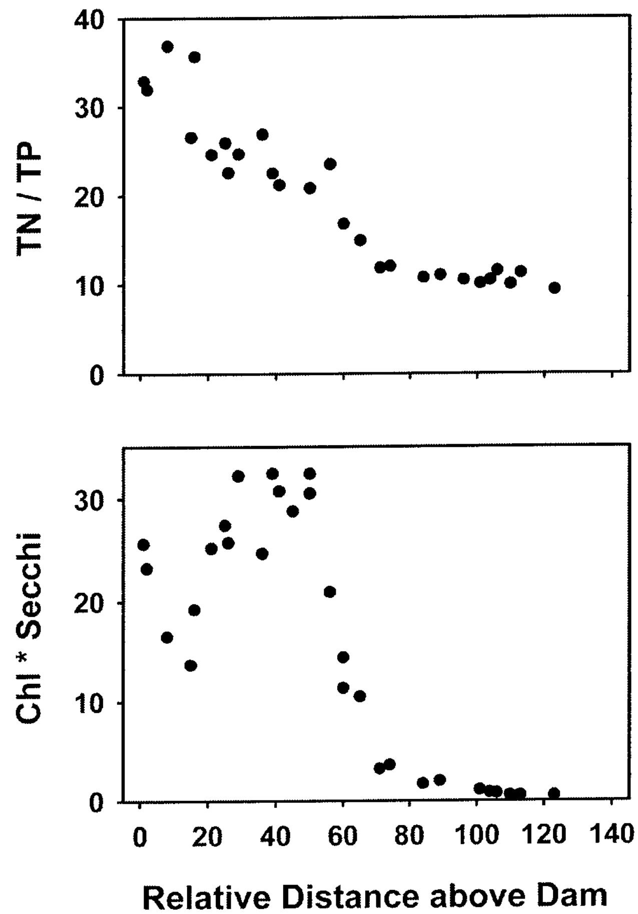


Figure 6. Longitudinal gradients in the ratio of total nitrogen to total phosphorus (weight/weight; upper), and the product of chlorophyll concentration and Secchi depth (mg/m^2) in West Point Lake surface waters during September 1991. Based on data reported by Kennedy et al. (1994)

extinction between algae and inorganic turbidity (Walker 1996), exhibits a dramatic increase at mid-reservoir. This indicates a shift from a turbidity-dominated to an algae-dominated light regime.

Together, these observations suggest that the development of nutrient criteria must address issues of spatial heterogeneity. Clearly, conditions influencing trophic responses can change, often dramatically, within a single reservoir. In the case of West Point Lake, it would be unreasonable to expect uniform responses throughout the lake. For instance, phosphorus reductions, in the absence of commensurate reductions in inorganic turbidity, would not result in the otherwise anticipated reduction in chlorophyll in the light-limited upstream reaches of the lake.

What Analytical Methods Are Most Appropriate for Identifying Reference Conditions and Developing Nutrient Criteria for Corps Reservoirs? Regardless of the method used to group them based on similarities in non-nutrient characteristics, the development of nutrient criteria for reservoirs will be limited to two basic approaches: frequency analysis of current or historical data; and the use of water quality models. The relatively recent construction of dams, and

the fact that reservoir basins are inundated river floodplains, precludes meaningful paleolimnological reconstruction of historical water quality conditions.

Frequency analysis involves determining the characteristics (e.g., central tendency and variability) of the distribution of individual observations of trophic state variables (e.g., total phosphorus or chlorophyll concentration). This approach to identifying reference conditions assumes that reservoirs in the upper percentiles of the distribution are of highly acceptable water quality and can represent a reference condition toward which to manage. The value of the analysis is obviously sensitive to the number of observations included. In this regard, frequency analyses should be used carefully for many of the regions in which reservoirs are located, since the number of reservoirs and related water bodies included in the analysis will often be limited (see the ecoregional distribution of Corps reservoirs displayed in Figure 1). As an example, there are a limited number of mainstem storage reservoirs on the Cumberland River (see discussion above). If their location in the hydrologic continuum and/or their operational characteristics place them in the same group, frequency analyses would provide little useful information due to the limited size of the sampled population.

Water quality models portray changes in trophic state variables in response to changes in nutrient loading using either mechanistic descriptions of processes or empirical relationships. Both types of models have been successfully employed for assessments of eutrophication-related phenomena in lakes and reservoirs (e.g., Ernst, Frossare, and Mancini (1994), Kennedy (1995)), and offer potentially valuable tools for identifying reference conditions for Corps reservoirs. The approach involves confirmation of a particular model's ability to adequately portray observed water quality conditions and its subsequent use to estimate water quality conditions given changes in loading conditions.

BATHTUB (Walker 1996), an empirical eutrophication modeling framework based on an extensive Corps-wide assessment of reservoir water quality (Walker 1985), was applied to West Point Lake (see description above) as a means to demonstrate this approach. The model was first applied based on observed nutrient loading and in-reservoir water quality data as a means to evaluate performance. Loading conditions were then modified to reflect average 'background' nutrient conditions for U.S. rivers as recently reported by the U.S. Geological Survey (1999). Results displayed in Figure 7 include estimated average growing season means for nutrients (phosphorus and nitrogen), chlorophyll concentration, and Secchi depth for previous years and as predicted for background loading conditions. Given the assumptions of this example, lowered trophic responses to background levels of nutrient loading could provide a basis upon which to establish a reference condition.

Since, as was previously described, reservoirs often exhibit pronounced lateral or longitudinal gradients in water quality responses, models for estimating trophic responses must address spatial heterogeneity. The importance of this requirement is apparent based on BATHTUB model results displayed in Figure 8. The establishment of a longitudinal series of model segments allowed portrayal of spatial differences in trophic responses in West Point Lake. As above, responses for two previous years and those estimated to occur given background loading rates were compared. There are clear spatial differences in trophic response under each of the three loading conditions. Of interest here is the observation that algal production exhibits the greatest variation in response

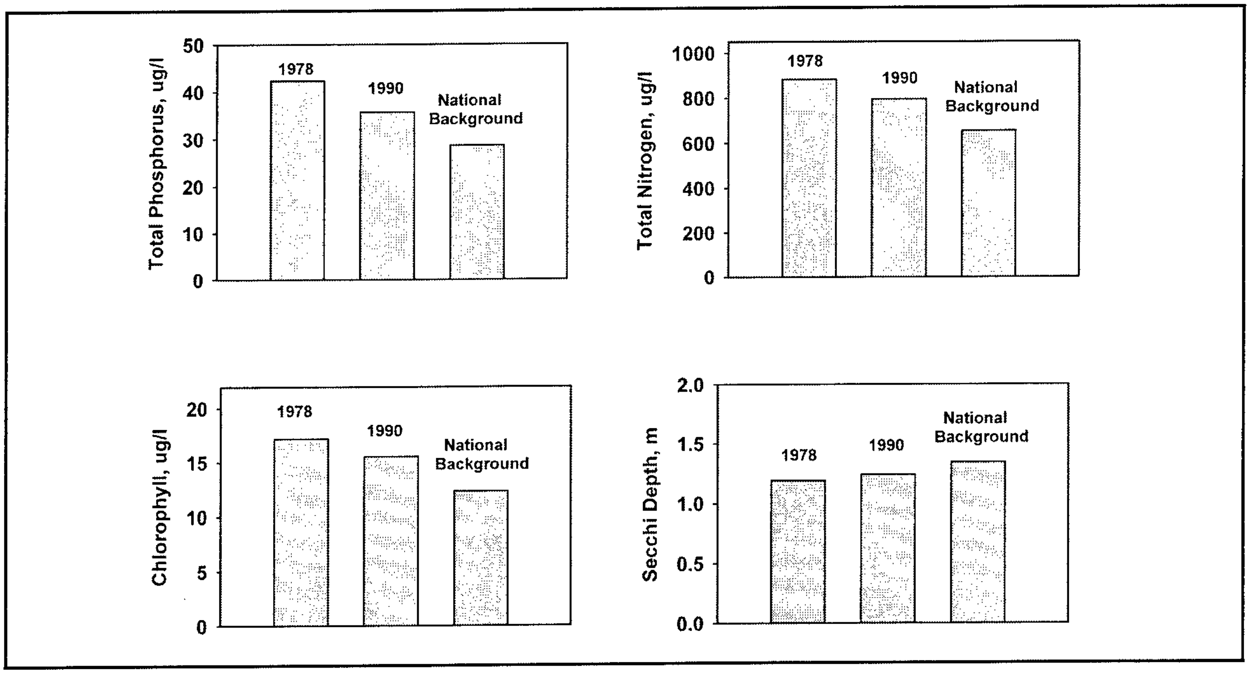


Figure 7. Predicted lake-wide average trophic responses for the growing season (May-September) in West Point Lake to nutrient loading levels observed in 1978 and 1990, and those corresponding to the estimated national background levels for rivers and streams (based on data reported in U.S. Geological Survey (1999)) (Predictions based on application of the eutrophication model BATHTUB (Walker 1996))

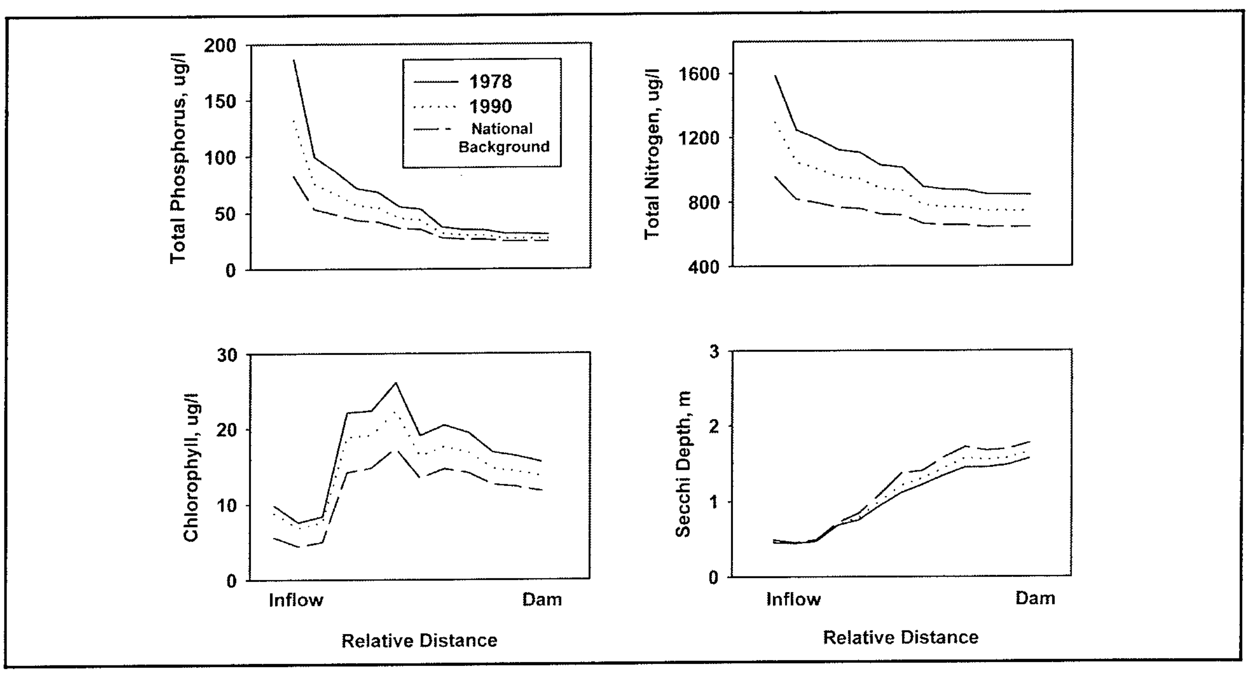


Figure 8. Predicted longitudinal gradients in trophic conditions during the growing season (May-September) in West Point Lake in response to nutrient loading levels observed in 1978 and 1990, and those corresponding to the estimated national background levels for rivers and streams (based on data reported in U.S. Geological Survey (1999)) (Predictions based on application of the eutrophication model BATHTUB (Walker 1996))

in the central region of the reservoir, which may have significant management implications and would have been overlooked had the model not addressed spatial heterogeneity.

Since Reservoirs Serve as Material Sinks, Should Selected Reservoirs Within a Watershed Be Assigned Nutrient Criteria That Acknowledge This Function? Reservoirs are important and effective traps of nutrients and sediments (e.g., Kennedy (1998), Straškraba et al. (1995)). As such, they are often significant in the regulation of the material budgets of entire drainage basins. The potential importance of total phosphorus retention by reservoirs and its modifying influence on riverine nutrient budgets are demonstrated by water quality data for a three-reservoir cascade on the White River in northwestern Arkansas and southern Missouri. The three Corps reservoirs, Beaver Lake, Table Rock Lake, and Bull Shoals Lake, exhibit differing water residence times and phosphorus retention rates, and, despite their close proximity on the same river, receive inflows with markedly different total phosphorus concentrations due to variations in loads from point and nonpoint sources (Figure 9). Beaver Lake receives inflows with relatively high total phosphorus concentrations, owing to agricultural land uses, but retains approximately 74 percent of the phosphorus load and releases water with markedly reduced total phosphorus concentrations. Upstream reaches of the reservoir exhibit high algal production and reduced water clarity, due to ample availability of nutrients, while low algal production and increased water clarity are observed in downstream reaches coincident with declining nutrient availability.

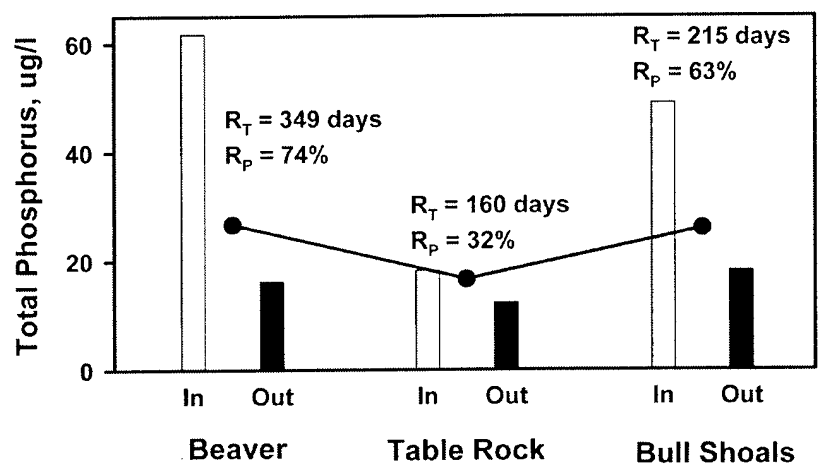


Figure 9. Average inflow and outflow total phosphorus concentrations (vertical bars) and in-reservoir total phosphorus concentration (solid circle) for Beaver, Table Rock, and Bull Shoals Lakes on the White River, AR. R_T and R_P indicate water residence time (days) and total phosphorus retention (percent), respectively

Table Rock Lake, the next downstream reservoir in the cascade, benefits from phosphorus retention in Beaver Lake and receives inflows with relatively low total phosphorus concentrations. While release total phosphorus concentrations below Table Rock Lake are low, loading rates to the river are high immediately upstream from Bull Shoals Lake and total phosphorus concentrations are again elevated. However, the high rate of total phosphorus retention in Bull Shoals Lake (63 percent) again reduces total phosphorus concentrations in the White River below the dam. The net effect of the three-reservoir cascade is modulation of total phosphorus concentrations along this 200-km

reach of the White River through phosphorus retention. In the absence of the three reservoirs, and given the high rates of total phosphorus loading to the river, concentrations higher than those observed would be anticipated.

Kennedy (1998) reports that phosphorus retention by reservoirs is a function of water residence time and areal phosphorus loading rate (Figure 10), and that such retention has important implications for the phosphorus budgets of drainage basins. As demonstrated above for the White River, reservoirs can be viewed as nutrient sinks within a drainage basin and may serve to reduce loadings to downstream water resources, including other reservoirs. In the context of nutrient criteria, the value of this function for reservoirs should be a topic of discussion, since reservoirs identified as nutrient sinks may experience water quality conditions (e.g., high nutrient concentrations) that differ from those otherwise anticipated or desired. Nutrient criteria for such lakes could be modified accordingly.

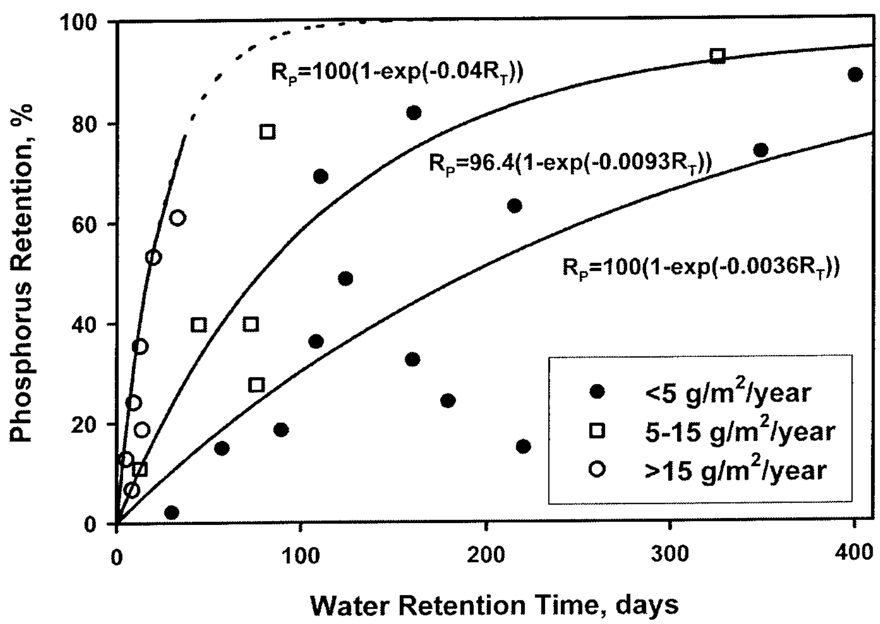


Figure 10. Relationship between total phosphorus retention and and water residence time values for selected Corps reservoirs with differing areal phosphorus loads. Curves and associated equations estimate relationships between total phosphorus retention (R_P) and water residence time (R_T) for each of three areal phosphorus loading categories (Kennedy 1998).

CONCLUSIONS: This technical note discussed a range of issues and considerations for application of the EPA's proposed approach for the development of nutrient criteria for lakes and reservoirs, with particular concern for Corps reservoirs. The following conclusions were reached:

1. Reservoirs exhibit diverse morphometric, hydrologic, and operational characteristics that strongly influence their response to nutrients. Such characteristics must be considered in the development of nutrient criteria for Corps reservoirs.

2. While differing in origin from natural lakes, reservoirs should not be distinguished solely by the presence of a dam. In some cases, reservoirs may be reasonably included with selected lakes when identifying nutrient criteria.

3. Water quality models offer a reasonable approach to estimating reference conditions, particularly when the number of reservoirs in a region limits statistical evaluations of observed data.

4. The development of nutrient criteria should account for spatial differences in the expression of trophic responses to nutrients.

5. Development of nutrient criteria should acknowledge the functional role played by reservoirs within drainage basins.

RECOMMENDATIONS: The proposed development of nutrient criteria for lakes and reservoirs raises a number of difficult questions for the Corps, but also provides new and unique opportunities. The Corps' water resource development mission, while acknowledging the linkage between watershed and reservoir, and between reservoir water quality and tailwater quality, has historically been confined to the spatial and operational limits of a particular project and its immediate watershed. The Corps has thus had little direct recourse to ensure that waters entering a project do not adversely impact water quality. While engaging in dialog with federal, state, and local regulatory agencies as a means to encourage improved water quality through reduced material loadings, Corps water quality management efforts have traditionally focused on structural or operational strategies designed to improve release water quality. Since linkages between watershed processes and water quality responses are explicit in nutrient criteria for lakes and reservoirs, their development offers a unique opportunity for the Corps to engage in a meaningful relationship with watershed partners to address the broadest possible range of nutrient-related water quality issues.

Realizing this opportunity will require that the Corps become an active and knowledgeable partner in the nutrient criteria development process. To successfully accomplish this, Corps District and Division water quality management personnel must:

1. ***Understand the process***. Corps water quality personnel must become familiar with the process by which states will establish nutrient criteria, since such criteria will directly influence the Corps' water resource development missions and objectives.

2. ***Participate in the dialog.*** The active and informed participation of Corps personnel in the development of nutrient criteria will ensure that Corps interests are fully represented and that Corps experiences/expertise are available to watershed partners.

3. ***Identify, compile and share appropriate data.*** Access to Corps water quality, and particularly water control data will be essential if the nutrient criteria development process is to adequately address nutrient criteria issues for Corps reservoirs. The Corps must also participate in the design and conduct of efforts to collect new data when required.

4. ***Participate in data analyses and criteria development.*** Corps participation in analyses of information related to reservoirs provides a functional and administrative link between Corps mission objectives and the establishment of nutrient criteria.

5. ***Assess success.*** Environmental management and restoration efforts must include a means by which to gauge or evaluate success. The Corps must address this need in all future water resource management activities, particularly as related to the control of eutrophication.

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